EFFECTS OF THERMAL MODIFICATION ON MECHANICAL AND SWELLING PROPERTIES AND COLOR CHANGE OF LUMBER KILLED BY MOUNTAIN PINE BEETLE

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To extend the application of mountain pine beetle (MPB) killed lumber for decking, siding, and landscaping materials, it is essential to improve its dimensional stability. Thermal treatment is one of the well-established processes used to improve wood stability by modifying chemical compounds and masking blue-stains by darkening the fibre color. In this study, the MPB lumber was subjected to thermal treatment at three temperatures (195, 205, or 215°C) and three exposure times (1.5, 2, or 3 h). Based on Duncan's multiple range test, the results indicated that the volumetric swelling after thermal treatment, either from oven-dry to air-conditioned or from oven-dry to water-saturated, was significantly reduced after thermal treatment. Modulus of elasticity was increased when specimens were treated at a temperature of 195°C, and then decreased as the temperature increased. Modulus of rupture was significantly reduced as treatment temperature increased. The hardness of lumber thermal-treated at 195°C was significantly increased compared to that of the untreated lumber. At higher temperatures, hardness started to decrease slightly. With the treatment temperature increasing to 215°C for 3 h, the color difference between stained and clear wood was reduced by 75%. As a result, the blue-stains vanished gradually.

Keywords: Mountain pine beetle; Thermal treatment; Dimensional stability; Mechanical properties

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INTRODUCTION

The mountain pine beetle (MPB) epidemic has killed millions of lodgepole pine (*Pinus contorta* Douglas var. *latifolia* Engelmann) trees in British Columbia, Canada (Rice and Langor 2009) and blue-stain fungi often cause blue stains in the killed trees (Rice *et al.* 2007). It is estimated that 80% of the merchantable pine volume will be dead by 2017 (British Columbia Ministry of Forests and Range 2007). Although MPB lumber products are acceptable in the North American markets, consumer concerns about blue-stains caused by MPB are increasing. In the Japanese market, MPB lumber exports were reduced because of the reluctance to accept lumber with blue stains. Furthermore, current lumber quality requirements are more stringent due to the strong competitive lumber product market. To meet the growing market demand for quality wood products, it is extremely important to pursue any new market opportunity for MPB lumber.

To extend the application of MPB lumber for decking and siding materials, as well as landscaping items, it is necessary to improve its dimensional stability and mask

the blue-stains. As an environmentally responsible technology, thermal modification is one of the most well-established, chemical-free processes used for improving physical properties of wood. Thermal modification alters the chemical compounds permanently through a high temperature treatment (Boonstra and Tjeerdsma 2006; Metsa-Kortelainen *et al.* 2006; Akgul *et al.* 2007; Yilgor and Kartal 2010; Gunduz *et al.* 2010). Compared to kiln-dried wood, the dimensional stability of the thermally modified wood, with respect to tangential and radial swelling, is considerably improved, due to its lower equilibrium moisture content. The reduced permeability and the amount of fungi-susceptible material result in well-behaved biological durability in the thermally modified wood. In addition, the blue-stains can be masked by darkening the fibre color.

Bekhta and Niemz (2003) found that the thermal treatment resulted in darkened wood tissues, improved dimensional stability, and reduced mechanical properties. The darkening was accelerated generally when treatment temperature exceeded approximately 200°C. A decrease in modulus of rupture (MOR) was as great as 44 to 50%, while a reduction in modulus of elasticity (MOE) was only 4 to 9% due to the thermal treatment. The regression analysis indicated that the color difference strongly correlated to both MOE and MOR. Thus, the color parameters can be used as a prediction of wood strength.

Kocaefe *et al.* (2008) reported that the thermally treated wood became less hygroscopic due to decomposition of hemicelluloses and crystallization of cellulose. Using a thermogravimetric analyzer, the effect of thermal modification conditions, *i.e.* treatment temperature, heating rate, exposure time, and the gas humidity on the mechanical properties of North American jack pine were examined (Kocaefe *et al.* 2010). The results showed that the change in bending strength, hardness, screw withdrawal strength, and dimensional stability of jack pine depended on the treatment conditions. This suggests that selecting the proper treatment conditions should be prioritized. Cao *et al.* (2012) found that MOR, MOE, and hardness of Chinese fir sapwood increased while treatment temperatures remained below 200°C for short treatment times. Once the treatment temperatures exceeded 200°C, mechanical properties were significantly reduced. Karlsson *et al.* (2011) investigated the influence of heating media (vegetable oils and steam) used in thermal modification on the durability and water resistance of several wood species (European aspen, Norway spruce, and Scots pine). It was found that the fungal resistance was excellent for aspen, spruce, and pine when thermally modified in linseed oil for 1 h at 200°C. Satisfactory fungal resistance during a rot test was also found in spruce and pine when thermally modified in saturated steam at 180°C.

Tumen *et al.* (2010) examined the chemical structural changes in the thermally treated (170, 190, and 210°C for 4, 8, and 12 h) hornbeam and Uludag fir wood. The results showed that several chemical structures in the treated wood were permanently changed due to the thermal degradation of wood polymers. The decrease in the cellulose and holocelluloses ratio played a favourable role on the interaction of the wood with moisture. The maximum decreases in holocellulose and α-cellulose and the maximum increase in lignin were found at 210°C for 12 h. It was concluded that the thermally treated Uludag fir wood can be used for saunas, pool edges, siding, ship decks, and garden furniture. Thermal treatment resulted in lighter wood, making it useful in applications such as insulation and parquet flooring. Stanzl-Tschegg *et al.* (2009) reported that thermal modification significantly improved hardness properties in the longitudinal direction of beech wood. Standfest and Zimmer (2008) also found that the

hardness in longitudinal direction of thermally treated European beech and ash was higher than that of the untreated ones. The hardness values in the radial and tangential direction became smaller during intensive thermal treatment.

It is of interest to control the color changes during heat treatment, which can have an effect on wood appearance and strength. Sundqvist (2002) investigated the color changes for Scots pine, Norway spruce, and birch wood during heating. Birch responded faster and more markedly in color difference than pine and spruce, which was believed to be associated with the general difference in hemicellulosic content between softwoods and hardwoods, and the often characteristic composition of phenolic extractives for certain species. Both treatment time and temperature showed influence on the color responses for pine and spruce, which was influenced mostly by temperature. Sundqvist and Moren (2002) reported that both polymers (hemicelluloses and lignin) and extractives participated in the color formation of wood subjected to hydrothermal treatment. Dubey *et al.* (2012) studied heat-treated *Pinus radiata* wood at 160 to 210°C in linseed oil and examined the effects of treatment on chemical composition, color, dimensional stability, and fungal resistance. It was found that the anti-swelling efficiency and fungal resistance were improved by up to 60% and 36%, respectively. The color of heat-treated wood was darker and more uniform as the treatment temperature increased. Leitch (2009) found that the black ash wood deepened in color from a light brown to a darker brown, similar to that of walnut wood, when it was thermally treated at a temperature of 200°C. The hardness of the thermally modified black ash displayed 43% greater than the controls.

This study was aimed at extending the application of MPB lumber for decking and siding materials, as well as landscaping items, by increasing the dimensional stability and reducing or eliminating the effect of blue-stains on lumber appearances through thermal treatment. Since the thermal treatment often brings about negative effects on mechanical properties, the MOE, MOR, and hardness of the treated wood were also examined. It was expected that the thermal treatment would be capable of converting low cost lumber into acceptable high-valued products.

MATERIALS AND METHODS

Lumber Specimens

Sourced from the Interior of BC, Canada, green MPB lodgepole pine lumber was kiln-dried to a moisture content of 10 to 19% and shipped to Nanjing, China. The specimens with a dimension of 38.5 × 89 × 1000-mm (thickness × width × length) were prepared for the thermal treatment. The experiments were carried out in the wood-drying laboratory in the Nanjing Forestry University, China.

Thermal Treatment Process

Equipped with electrical heaters and a small boiler, the laboratory thermal chamber with a capacity of one cubic meter was utilized in this study. The air velocity was pre-set at 10 m/s to provide adequate air circulation. The boiler supplied saturated steam to prevent the wood from burning. The air content was assumed to be lower than 3.5% during the thermal treatment. Three steps were carried out for the thermal treatment:

1. Drying: Using heat and steam, the dry/wet-bulb temperatures in the chamber were raised to 80°C in 2 h and remained constant for 1 h. Then, temperatures were increased to 100°C with a rate of 10°C/h and remained constant for 1 h. Solely the dry-bulb temperature was increased at a rate of 15°C/h until the thermal treatment temperatures, *i.e.* 195, 205, or 215°C were reached. Concurrently, specimens were dried to a moisture content of approximately 0%.
2. Thermal treatment: The chamber temperatures remained at 195, 205, or 215°C for 1.5, 2, or 3 h, respectively.
3. Cooling and equalization: With a water spray, the temperature was reduced to about 60°C and the equilibrium moisture content was increased to 6%. Specimens remained in the chamber for 24 h.

Measurements of Swelling

Based on the Chinese Standards (GB 1934.2-91), 20 swelling specimens with a size of 20 × 20 × 20-mm were tested for each set of treatment condition. By measuring the width, thickness, and length, the volumes of the oven-dry specimens (V_d) were calculated. The volumes of the specimens (V_a) were measured again after they were equilibrated in a humidity chamber with a temperature of 20±2°C and a relative humidity of 65±5%. The volumetric swelling values (%) from oven-dry to air-conditioned were calculated using Equation (1):

$$\alpha_{Va} = (V_a - V_d)/V_d \times 100 \quad (1)$$

The specimens were placed in distilled water at 20°C for 20 days until stable volumes were obtained. The volumes of the water-saturated specimens (V_w) were determined again. The volumetric swelling values (%) from oven-dry to water-saturated were calculated using Equation (2):

$$\alpha_{Vw} = (V_w - V_d)/V_d \times 100 \quad (2)$$

Measurements of the Mechanical Properties

To assess the effect of thermal treatment on mechanical properties, MOR, MOE, and hardness for untreated and thermal-treated specimens were measured using the CMT 4202 Universal Test Machine. Specimens were placed in a conditioning chamber with a relative humidity of 65% at a temperature of 20°C for 4 weeks before the tests.

MOE and MOR were measured in bending using a third-point loading test according to ASTM D-143 (2004). Twenty bending specimens with a size of 20 × 20 × 250-mm were tested for each set of treatment condition. A load rate of 150 mm/min was used. To ensure repeatability of the stiffness test results, each specimen was loaded twice and then a third time to failure. The deflection was measured at the load points. The stiffness was calculated using linear regression analysis of the load *vs*. deflection data. The MOE value was calculated using the stiffness and the measured dimensions of each specimen. The MOR value was calculated using the failure load and the measured dimensions of each specimen. Hardness tests were performed in accordance with ASTM D-1324-83 (2004). Under the maximum force of 400 N, 20 specimens with a dimension of 50-mm × 50-mm × 250-mm were tested for each set of treatment condition. A ball

with a diameter of 11.3 mm and a penetration rate of 6 mm/min were used. The load was applied to tangential surfaces and perpendicular to the wood grain.

Measurements of Color

Color measurements were carried out before and after thermal treatment with the colorimeter Color Reader CR-10. Since only one color variable is required to represent hue, the $L^*C^*h^\circ$ system was selected to describe the color changes (Bekhta and Niemz 2003). In this system, L^* indicates the lightness, and the other two parameters can be calculated from the chromaticity coordinates a^* and b^*, corresponding to the green-red and blue-yellow axis, respectively.

From the $L^*a^*b^*$ values, hue angle (h°), and chroma or saturation (C^*) were obtained using Equations (3) and (4):

$$h^\circ = arctan\frac{b^*}{a^*} \quad (3)$$

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (4)$$

The total color difference (ΔE^*_{ab}) between blue-stains and clear wood was calculated using Equations (5) and (6),

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (5)$$

$$\Delta L^* = L^*_c - L^*_b;\ \Delta a^* = a^*_c - a^*_b;\ \Delta b^* = b^*_c - b^*_b \quad (6)$$

where L^*_c, a^*_c, and b^*_c are L^*, a^*, and b^* of the clear wood; and L^*_b, a^*_b, and b^*_b are L^*, a^*, and b^* of the blue-stained zones, respectively.

Twenty replicates were measured for each set of treatment condition.

RESULTS AND DISCUSSION

Swelling Properties

As a function of treatment temperature and time, Table 1 presents the results of volumetric swelling tests of the thermally treated wood. Compared to the untreated wood, the volumetric swelling values from oven-dry to air-conditioned or to water-saturated were reduced substantially through the thermal treatment at any combination of temperature and exposure time.

As the treatment temperature increased from 195°C to 215°C, the swelling was reduced from 22.6% to 31.9% for air-conditioned specimens and from 16.4% to 25.9% for water-saturated specimens (Table 2). With an increase in exposure time from 1.5 h to 3 h, the volumetric swelling was reduced from 22.9% to 34.3% for air-conditioned specimens and from 15.3% to 24.8% for water-saturated specimens.

Table 1. Volumetric Swelling Values (%) of the Thermal Modified Lumber

Treatment Time and Temperature	1.5 h		2 h		3 h	
	Air-cond. α_{Va}(%)	Water-soak α_{Vw}(%)	Air-cond. α_{Va}(%)	Water-soak α_{Vw}(%)	Air-cond. α_{Va}(%)	Water-soak α_{Vw}(%)
Control	5.38 (0.71)	15.08 (2.05)	5.38 (0.71)	15.08 (2.05)	5.38 (0.71)	15.08 (2.05)
195℃	4.29 (0.56)	13.05 (1.80)	4.24 (0.55)	12.54 (1.83)	3.96 (0.44)	12.22 (1.69)
205℃	4.12 (0.53)	12.75 (1.79)	4.02 (0.55)	11.75 (1.89)	3.62 (0.41)	11.57 (1.60)
215℃	4.03 (0.47)	12.51 (1.54)	3.94 (0.61)	10.81 (1.78)	3.03 (0.45)	10.22 (1.61)

- Values in parentheses are standard deviations
- α_{Va}(%) and α_{Vw}(%) are the volumetric swelling values from oven-dry to air-conditioned and to water-saturated, respectively

Hydrophilicity of thermally treated wood was reduced by breaking down hemicelluloses, modifying lignin, and decreasing the number of hydroxyl groups in the wood cell walls (Akgul *et al*. 2007). Water repellent compounds block macro pores by depositing hydrophobic substances in the cell lumen. As a result, the thermal treatment decreased water uptake, resulting in a lower swelling effect (Ahmed and Moren 2012). In this study, it was confirmed that when higher temperatures or longer times were used in the treatment, more hemicelluloses were broken down and lower swelling was obtained.

In order to statistically evaluate the reduction in swelling under different treatment temperatures and times, Duncan's multiple range test (MRT) was used in the analysis (Seville 2003). MRT is a multiple comparison procedure developed by Duncan (1955), which is used to determine whether three or more means differ significantly in an analysis of variance. Table 2 presents the volumetric swelling, both from oven-dry to air-conditioned (α_{Va}) and from oven-dry to water-saturated (α_{Vw}), and Duncan's MRT results for different treatment temperatures and times. It shows that the volumetric swelling, either α_{Va} or α_{Vw}, was significantly reduced after the thermal treatment at any temperature/time ($p<0.05$).

Table 2. Multi-Comparison of Swelling under Different Temperatures and Times

Treatment Condition		Air-cond.			Water-soak		
		α_{Va} (%)	MRT	Reduction (%)	α_{Vw} (%)	MRT	Reduction (%)
Temp.	Control	5.38	A	-	15.08	A	-
	195℃	4.16	B	22.61	12.60	B	16.42
	205℃	3.92	B	27.14	12.02	B	20.27
	215℃	3.67	C	31.85	11.18	C	25.86
Time	Control	5.38	A	-	15.08	A	-
	1.5 h	4.15	B	22.92	12.77	B	15.32
	2 h	4.07	B	24.41	11.70	C	22.41
	3 h	3.54	C	34.26	11.34	C	24.82

- α_{Va}(%) and α_{Vw}(%) are the volumetric swelling values from oven-dry to air-conditioned and to water-saturated, respectively.
- MRT is the Duncan's multiple range test (groups with the same letters in each column indicate that there is no statistical difference ($p<0.05$) between the samples).
- Reduction is the swelling reduced in comparison with the control.

MOE, MOR, and Hardness Properties

Table 3 presents the mean values and standard deviations of MOE, MOR, and hardness under different treatment temperatures and times. MOE increased when the specimens were treated at 195°C. Then it decreased as the temperature increased further. When the treatment temperatures were 205°C and 215°C, compared to those of the untreated sample, the MOE of the treated lumber was reduced by 4.39% and 5.51%, respectively (Table 4). Similar findings were reported for jack pine by Kocaefe *et al.* (2010) and for Chinese fir by Cao *et al.* (2012). Table 4 shows that MOE increased when the exposure time of 1.5 h was used. However, as the longer exposure times (2 h and 3 h) were used, MOE was reduced by 4.28% and 5.24%, respectively. As seen in Table 4, MOR was reduced by 10.13%, 20.23%, and 24.02% when the treatment temperatures of 195°C, 205°C, and 215°C were utilized. As the exposure time increased from 1.5 h to 3 h, MOR was reduced from 13.22% to 25.12%.

Table 3. Changes in MOE, MOR, and Hardness after Thermal Treatments

Treatment Time and Temperature	MOE (MPa)			MOR (MPa)			Hardness (MPa)		
	1.5 h	2 h	3 h	1.5 h	2 h	3 h	1.5 h	2 h	3 h
Control	10110 (1646)	10110 (1646)	10110 (1646)	114.5 (16.8)	114.5 (16.8)	114.5 (16.8)	11.82 (1.51)	11.82 (1.51)	11.82 (1.51)
195℃	11860 (1520)	9783 (1369)	9691 (1421)	104.6 (21.4)	106.1 (18.2)	98.0 (19.2)	13.3 (1.44)	12.1 (1.59)	12.8 (1.69)
205℃	9726 (1522)	9664 (1322)	9610 (1298)	98.6 (15.6)	92.2 (17.6)	83.2 (18.6)	12.4 (1.48)	11.8 (1.29)	11.6 (1.36)
215℃	9632 (1476)	9586 (1401)	9441 (1368)	94.9 (15.8)	90.1 (14.9)	76.0 (16.8)	10.9 (1.32)	12.5 (1.43)	11.9 (1.43)

- Values in parentheses are standard deviations.

Table 4. Multi-Comparison of MOE, MOR, and Hardness at Different Conditions

Treatment Condition		MOE (MPa)			MOR (MPa)			Hardness (MPa)		
		Mean	MRT	Rd.(%)	Mean	MRT	Rd.(%)	Mean	MRT	Rd.(%)
Temp (°C)	Control	10110	A	-	114.5	A		11.82	A	-
	195	10445	B	-3.31	102.9	B	10.13	12.73	B	-7.73
	205	9667	C	4.39	91.3	C	20.23	11.93	A	-0.96
	215	9553	C	5.51	87.0	D	24.02	11.77	A	0.45
Time (h)	Control	10110	A	-	114.5	A	-	11.82	A	-
	1.5	10406	B	-2.93	99.4	B	13.22	12.20	B	-3.21
	2	9678	C	4.28	96.1	B	16.04	12.13	B	-2.65
	3	9581	C	5.24	85.7	C	25.12	12.10	B	-2.37

- MRT is the Duncan's multiple range test (groups with the same letters in each column indicate that there is no statistical difference ($p<0.05$) between the samples).
- Rd. is the reduction compared to the values of the control specimens.

The observed loss in mechanical properties has been explained as the result of hemicellulose degradation, increased crystalline cellulose content, and the replacement of flexible hemicellulose–cellulose–hemicellulose bonds with more rigid cellulose–cellulose bonds (Kocaefe *et al.* 2010). Due to its amorphous structure, the hydroxyl groups in hemicellulose have higher accessibility to water than cellulose. The proportion of crystalline components in wood increased because of the removal of hemicelluloses.

Wood flexibility decreased as the flexible hemicellulose-cellulose-hemicellulose bonds were replaced by rigid cellulose-cellulose bonds during the thermal treatment. A decrease in elasticity occurred due to the decomposition of the long-chained polymers in the wood's molecular structure, resulting in more fragile wood (Korkut and Budakci 2009).

Duncan's MRT indicated that MOE significantly increased after a treatment at 195°C for 1.5 h (Table 4). As the temperature or the exposure time increased, MOE was significantly reduced as shown in Table 4. No significant reduction in MOE was found when the temperature increased from 205°C to 215°C or the exposure time from 2 h to 3 h. Table 4 also shows that MOR was significantly reduced as the treatment temperature was increased to 195, 205, or 215°C. Although no significant reduction in MOR was discovered when the exposure time was increased from 1.5 h to 2 h, a significant reduction was observed when the exposure time was increased from 2 h to 3 h.

The variation of the hardness with the treatment temperatures and exposure time is presented in Table 3. At a temperature of 195 °C, thermally-treated lodgepole pine was found to be harder than the untreated wood (an increase of 7.73%). At higher temperatures, hardness gradually decreased. Duncan's MRT showed that, compared to that of untreated wood, a significant increase in hardness was observed when the treatment temperature of 195°C was used (Table 4). As temperature increased, the hardness was reduced. No significant differences in hardness were found between the untreated wood and that treated at temperatures of 205°C and 215°C. When the MPB lumber was treated at a temperature of 195°C, the heat-treated lumber was found to be harder than the untreated wood. At this temperature, the components in wood were solely dried, but not chemically transformed, which increased the rigidity (Kocaefe *et al.* 2010). At higher temperatures, hardness started to decrease gradually. This is probably due to thermal degradation, which can start above 200°C (Leitch 2009).

Color Response

It was visually observed that the surfaces of lumber were darkened with an increase in treatment temperature. As a result, the blue-stains vanished gradually. Table 5 presents the average lightness values (*L**) measured from stained and clear wood for each specimen before and after the treatments.

Table 5. Difference in Lightness *L** between Stained and Clear Wood

Temperature (ºC)	Time (h)	Before treatment			After Treatment		
		Stained wood	Clear wood	Diff.(%)	Stained wood	Clear wood	Diff.(%)
195	1.5	74.1	80.9	8.4	59.5	60.1	1.0
	2	72.3	79.3	8.9	58.0	57.2	1.3
	3	71.7	78.7	8.8	58.6	59.1	1.0
205	1.5	72.0	80.2	10.2	49.7	48.8	1.8
	2	72.4	79.4	8.7	47.5	46.3	2.4
	3	72.9	81.2	10.2	46.5	45.5	2.3
215	1.5	70.4	79.0	10.8	48.6	47.9	1.4
	2	71.8	80.0	10.2	45.5	44.2	2.7
	3	73.1	80.9	9.6	42.9	41.9	2.4
Average absolute difference				9.5			1.8

- Diff. = (Clear wood L* - Stained wood L*)/Clear wood L*×100

Increase in treatment temperature tends to decrease L^* to approximately 40%. The maximum loss of lightness was approximately 45% after 3 h treatment at 215 °C, reaching a very low value (42.9 and 41.9 units) compared with 73.1 and 80.9 units for the untreated wood. This reduction in lightness was believed to be associated with the general difference in hemicellulosic content after the treatments (Sundqvist 2002). The lightness (L^*) changes of stained and clear wood, with respect to treatment temperature and exposure time, are listed in Table 5. The differences in lightness between the stained and clear wood were reduced from 9.5% to 1.8% after the thermal treatment.

Table 6. Reduction in ΔE^*_{ab} between Stained and Clear Wood after Treatments

Temperature (ºC)	Time (h)	Un-treated	Treated	Reduction (%)
195	1.5	10.3	5.2	49.64
	2	11.1	4.8	56.44
	3	10.3	4.5	55.87
205	1.5	12.7	4.5	64.22
	2	11.2	4.6	58.87
	3	12.7	4.1	67.53
215	1.5	13.5	4.0	70.02
	2	12.3	3.2	73.94
	3	11.5	2.8	75.42

The color differences (ΔE^*_{ab}) between stained and clear wood are illustrated in Table 6. ΔE^*_{ab} was found to depend on the treatment temperature and time. With treatment temperature increasing to 215°C for 3 h, the total color difference ΔE^*_{ab} was reduced from 11.5 to 2.8 units (Table 6), which was a reduction of 75%. Since a color difference (ΔE^*_{ab}) greater than around 2 to 3 units could be considered to be the limit of the human eye's ability to distinguish a difference (Sundqvist 2002), blue-stained lumber will be accepted by consumers after thermal treatment at a temperature of 215 ºC for 3 h.

Strong correlations were found between the average color lightness and both MOR and MOE after thermal treatment. A logarithmic relationship between MOR and color lightness L^* was obtained as follows:

$$MOR = 52.987 \times Ln(L^*) - 114.05 \qquad (R^2 = 0.8646) \qquad (7)$$

A linear relationship between MOE and color lightness L* was developed:

$$MOE = 16.768 \times L^* + 8817.9 \qquad (R^2 = 0.9384) \qquad (8)$$

These results suggested that MOR and MOE after thermal treatment can be predicted using the average L^* values on the surface of lodgepole pine lumber.

CONCLUSIONS

Lodgepole pine lumber affected by the mountain pine beetle (MPB) was thermally treated at three temperatures (195, 205, and 215°C) and three exposure times (1.5, 2, and 3 h). Swelling property, MOE, MOR, and hardness, as well as color responses, were examined experimentally. Based on Duncan's multiple range tests, the following conclusions were drawn from this project:

1. The volumetric swelling, either from oven-dry to air-conditioned or from oven-dry to water-saturated, was significantly reduced through thermal treatment. As the treatment temperature was increased from 195°C to 215°C, the volumetric swelling was reduced from 22.6% to 31.9% for air-conditioned specimens and from 16.4% to 25.9% for water-saturated specimens, compared to that of the untreated wood. With an increase in exposure time from 1.5 h to 3 h, the volumetric swelling was reduced from 22.9% to 34.3% for air-conditioned specimens and from 15.3% to 24.8% for water-saturated specimens.
2. MOE was increased when specimens were treated at 195°C, and then decreased as the temperature increased. When treatment temperatures were 205°C and 215°C, compared to those of the untreated wood, the MOE was reduced by 4.4% and 5.5%, respectively. MOR was reduced by 10.1%, 20.2%, and 24.0% when the treatment temperatures of 195, 205, and 215°C were used. As the exposure time was increased from 1.5h to 3h, the MOR was reduced from 13.2% to 25.1%.
3. The hardness of lumber thermal-treated at 195°C increased by 7.7% compared to that of untreated lumber. At higher temperatures, hardness started to slightly decrease.
4. The differences in lightness (L^*) between the stained and clear wood were reduced from 9.5% to 1.8% after the thermal treatment. The color difference (ΔE^*_{ab}) between stained and clear wood was also found to be dependent on the treatment temperature and exposure time. With the treatment temperature increasing to 215°C for 3 h, ΔE^*_{ab} was reduced by 75%. As a result, the blue-stains vanished gradually. It is possible to predict MOR and MOE after thermal treatment using the determined color lightness L^* on the surface of lodgepole pine lumber.

ACKNOWLEDGEMENTS

This work was supported by the State Forestry Administration of China through grant number 2011-4-12, the Science and Technology Department of Jiangsu Province, China, through grant number BC2011475 and the Forestry Innovation Investment (FII), British Columbia, Canada.

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Article submitted: April 26, 2012; Peer review completed: June 2, 2012; Revised version received and accepted: June 15, 2012; Published: June 20, 2012.